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Amputation effects on the underlying complexity within transtibial amputee ankle motion

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The presence of chaos in walking is considered to provide a stable, yet adaptable means for locomotion. This study examined whether lower limb amputation and subsequent prosthetic rehabilitation resulted in a loss of complexity in amputee gait. Twenty-eight individuals with transtibial amputation participated in a 6 week, randomized cross-over design study in which they underwent a 3 week adaptation period to two separate prostheses. One prosthesis was deemed "more appropriate" and the other "less appropriate" based on matching/mismatching activity levels of the person and the prosthesis. Subjects performed a treadmill walking trial at self-selected walking speed at multiple points of the adaptation period, while kinematics of the ankle were recorded. Bilateral sagittal plane ankle motion was analyzed for underlying complexity through the pseudoperiodic surrogation analysis technique. Results revealed the presence of underlying deterministic structure in both prostheses and both the prosthetic and sound leg ankle (discriminant measure largest Lyapunov exponent). Results also revealed that the prosthetic ankle may be more likely to suffer loss of complexity than the sound ankle, and a "more appropriate" prosthesis may be better suited to help restore a healthy complexity of movement within the prosthetic ankle motion compared to a "less appropriate" prosthesis (discriminant measure sample entropy). Results from sample entropy results are less likely to be affected by the intracycle periodic dynamics as compared to the largest Lyapunov exponent. Adaptation does not seem to influence complexity in the system for experienced prosthesis users. *© 2014 AIP Publishing LLC*.
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The amputation of a lower limb creates a major disruption to the neuromuscular system. The task of walking is now only possible through prosthetic rehabilitation. A lower limb prosthesis can help to transmit forces and energy. However, the natural stride-to-stride fluctuations that occur when walking are disturbed from a healthy walking pattern. In healthy, non-amputees, these stride-to-stride fluctuations have a deterministic nature that exhibits a rich complexity resembling mathematical chaos, a trait that is believed to provide increased functionality and adaptability. Stride-to-stride fluctuations are increased for individuals with amputation although a more appropriate prosthesis can improve these fluctuations. However, the possible changes in the underlying complexity are yet to be determined as this is only possible through surrogation techniques. Therefore, individuals with an amputation participated in a six week randomized, crossover study wearing a "more appropriate" and a "less appropriate" prosthesis for a three week period each. The individuals' ankle motions, while walking were analyzed with a motion capture system. Results showed that prosthetic ankle loses complexity compared to the sound ankle, but a "more appropriate" prosthesis improves complexity more than a "less appropriate" prosthesis. The loss of complexity in the prosthetic ankle exemplifies the obvious breakdown in the neuromuscular system. The improvement with a "more appropriate" prosthesis, however, reveals the potential for certain prostheses to be less of a hindrance in the accomplishment of a healthier gait pattern.

INTRODUCTION

Variability is an inherent phenomenon present within human movement (Bernstein, 1967; Stergiou and Decker, 2011). While initially under the guise of noise and error (Schmidt, 2003), more recent studies have shown human movement variability to have a deterministic structure rather than just being noise (Decker *et al.*, 2010; Harbourne and Stergiou, 2003; Hausdorff, 2007; Jordan *et al.*, 2007a; Jordan *et al.*, 2007b; Jordan and Newell, 2008; Miller *et al.*, 2006; Stergiou and Decker, 2011). In fact, the dogma in movement science has shifted such that some variability is now being interpreted as a positive; means to allow adaptability and a richer movement repertoire from which to execute a single task (Decker *et al.*, 2011; Jordan *et al.*, 2007a; Jordan and Newell, 2008; Stergiou *et al.*, 2006; Stergiou and Decker, 2011). The determinism within the temporal structure of variability of healthy movement is considered highly complex (Lipsitz and Goldberger, 1992; Lipsitz, 2002). The loss of complexity is considered to be associated with a

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decline in health and functional status (Lipsitz and Goldberger, 1992; Lipsitz, 2002).

Complexity, in this case, signifies the presence of temporal variations in the steady state output of a healthy biological system that is algorithmically chaotic (Decker *et al.*, 2010). Chaos is used in this context within its mathematical definition, specifically relating to a dynamical system whereby asserting that the present state of a system is dependent upon and determined by the previous. Thus, it has a deterministic nature without random elements; yet the system is not fully predictable due to the possible fluctuations that are present. In gait, a single step is dependent upon the previous step, which impacts the next step; however, it is not entirely possible to predict the exact next step. Complexity represents the underlying physiological capability to make flexible adaptations to everyday stresses placed on the human body (Lipsitz, 2002). The complexity within a system can be analyzed through nonlinear analysis tools combined with a process known as surrogation. Such nonlinear tools include approximate entropy and its improved counterpart sample entropy (SampEn), the largest Lyapunov exponent (LyE), correlation dimension, and detrended fluctuation analysis (Stergiou *et al.*, 2013).

In previous work, Wurdeman *et al.* (2013b) reported increased LyE values at the prosthetic ankle compared to the sound leg ankle in transtibial level amputees. These results reflect altered dynamics occurring at the prosthetic ankle, which was previously correlated to individuals' prosthetic preference (Wurdeman *et al.*, 2013a). However, such an increase in LyE is only truly indicative of increased attractor divergence, or varied organization of the movement. A positive LyE value can be found as a result of the presence of chaos or noise (Cignetti *et al.*, 2012; Rosenstein *et al.*, 1993; Wolf *et al.*, 1985). As a result, findings of Wurdeman *et al.* (2013b) provide no insight on the complexity contained within the ankle joint motions. Such insight might provide information with regards to limitations in adaptability, which would be considered to potentially translate clinically as decreased functionality.

Wurdeman *et al.* continued their study of amputee dynamics by investigating the influence of an appropriate prosthesis as dictated by Medicare Functional Classification Level, as well as a suitable adaptation period (Wurdeman, 2013a). Similar to comparing prosthetic ankle motion to sound ankle and healthy control ankle motion (Wurdeman *et al.*, 2013b), a more appropriate prosthesis (MAP) yielded improved stride-to-stride fluctuations (i.e., nonlinear dynamics) compared to a less appropriate prosthesis (LAP) (Wurdeman, 2013a). This provides an interesting question as it is possible that not only are the stride-to-stride fluctuations improved with regards to attractor divergence, but it is also possible that the less appropriate prosthesis is being driven towards increased LyE due to increased random noise, whereas the more appropriate prosthesis has less random fluctuations and is being driven by a more deterministic system. For the adaptation portion of the study, a U-shaped quadratic trend in LyE for ankle motion was revealed for transtibial amputees (Wurdeman, 2013a). This behavior is one seen in motor learning accredited to freezing and subsequent freeing of dynamic degrees of freedom (Newell *et al.*, 2003; Vereijken *et al.*, 1992). However, underlying this motor learning may be the development of complexity as the system strives to enhance its adaptability.

Therefore, the purpose of this study was a retrospective analysis of Wurdeman (2013a) to determine the underlying complexity within transtibial amputee gait. It was first hypothesized that fewer individuals would show complexity in the prosthetic ankle compared to the sound ankle. It was also hypothesized that with a "more appropriate" prosthesis, a larger number of individuals would display complexity in the prosthetic ankle compared to when wearing a "less appropriate" prosthesis. These hypotheses were driven by the increased LyE values previously reported in these comparisons (Wurdeman *et al.*, 2013b; Wurdeman, 2013a). Finally, it was hypothesized that by the end of an adaptation period, more individuals would display complexity in the prosthetic ankle than at baseline. This was based on the premise that proper adaptation is encompassed by motor learning, and thus the system would shift towards a state of high complexity as it optimized.

METHODS

Participants

Twenty-eight individuals (22 males, 6 females) were consented for participation in this study as approved by the medical center's institutional review board (Table I). Inclusion criteria stated all individuals were required to (1) have a transtibial level amputation, (2) be able to walk nonstop for 3 min., (3) be able to commit to 2 separate 3 week adaptation periods, and (4) have had their current prosthesis longer than 1 month. Exclusion criteria stated all individuals could not: (1) currently have any ulcers on either the residual limb or the contralateral limb, (2) be impaired in their ability to provide informed consent due to cognitive condition, (3) wear an exoskeletal type prostheses or non-removable cosmetic covers (prevented exchanging of components without causing irreparable damage to the person's prosthesis), (4) have any major neuromuscular or musculoskeletal conditions affecting gait (i.e., stroke, Parkinson's disease, multiple

TABLE I. Subject demographics. Note all participants were above MFCL K2 level. Mean (SD).

Age (yrs)	Height (cm)	Mass (kg)	Time since amputation (yrs)	Self-selected speed (m/s)	Residual limb length (cm)	Cause of amputation
53.6 (11.3)	177.4 (8.0)	98.4 (19.3)	8.3 (9.2)	0.84 (0.37)	16.3 (4.4)	16 trauma, 8 vascular/diabetes, 2 cancer, and 2 infection

sclerosis), (5) have been previously classified by their physician as K1 or K0 level (Gailey *et al.*, 2002), or (6) currently have a poor fitting prosthesis. One individual did require the use of an articulated ankle-foot-orthosis on the sound leg for medial-lateral joint stabilization.

Procedures

Data collection procedures are originally described in Wurdeman *et al.* (Wurdeman, 2013a) but are summarized here briefly. Subjects partook in a 6 week, randomized-crossover adaptation protocol encompassing two separate 3 week periods (English *et al.*, 1995). All procedures (i.e., prosthesis modifications and data collections) occurred within the University's gait laboratory. At the initial visit, the subject's foot/ankle/pylon were removed distal to the socket and an alternate foot/ankle/pylon attached. Subjects wore their own previously fabricated socket and suspension fitted by their prosthetist. The alternate prosthesis design was considered either "more appropriate" or "less appropriate" based on whether the activity level of the foot matched the subject's Medicare Functional Classification Level. After each change out of components (i.e., at initial visit and crossover point), the prosthesis was aligned by a certified prosthetist. After proper alignment, gait analysis was performed. Gait analysis was then repeated at 1.5 and 3 weeks of wear. After 3 weeks of wear with the initial prosthesis, the crossover occurred and the components were swapped and subsequently re-aligned. Order of prosthesis wear was randomized. The wear and data collection procedures were repeated similarly for the second prosthesis as the initial prosthesis. This resulted in three data collections per prosthesis per subject.

The same procedure was utilized for all data collections. The subjects walked on the treadmill for 2 separate trials, each of which was 3 min. in duration at their self-selected preferred walking speed. Subjects were given at least 1 min. rest between trials to prevent fatigue. Only the initial trial was used for analysis except in cases, where during the first trial a problem was noted during collection (e.g., subject had small stumble, grabbed and released handrail throughout trial, etc.) or problem noted with trial in post-processing (e.g., retroreflective marker blocked from view of camera, etc.). Walking speed was established on the treadmill at the initial visit and then the same speed was used for all trials throughout the 6 weeks. Hand rail use was permitted if necessary but under the instructions not to place weight through their arm. If subjects chose to use the hand rail, they were asked to similarly use throughout all data collections. Subjects wore a tight fitting singlet-type uniform during all walking trials. Twenty-seven retro-reflective markers were placed on pre-defined anatomical locations on the lower limbs (Vaughan *et al.*, 1992; Wurdeman *et al.*, 2013a; Wurdeman *et al.*, 2013b) such that each segment had a minimum of three non-collinear markers to allow three dimensional relative joint angle calculations. On the prosthetic limb, markers were placed on analogous locations as the sound limb. Marker position data were recorded in three dimensions (12 camera system, 60 Hertz; Motion Analysis Corp., Santa Rosa, CA, USA). Ankle flexion/extension time series for the sound and prosthetic limbs were then calculated from the raw marker position data (Visual 3D, Germantown, MD, USA). For this study, only the ankle was focused on due to the significant findings at the prosthetic ankle previously reported (Wurdeman *et al.*, 2013a; Wurdeman *et al.*, 2013b; Wurdeman, 2013a; Wurdeman, 2013b).

In order to determine the underlying complexity within the joint flexion/extension time series, the process of surrogation was utilized (Miller *et al.*, 2006; Small *et al.*, 2001). Surrogation is a method by which underlying determinism contained within the original experimental time series is destroyed (Miller *et al.*, 2006). Nineteen surrogate time series are generated for each original time series, thereby yielding 20 time series per joint per trial (1 original plus 19 surrogates). Then under nonparametric testing, the values calculated from the discriminating statistic are put in rank-order, and if the original time series is either first or last it can be considered to be significantly different than the surrogate time series ($\alpha = 0.05$). However, in practice, it should be expected that the original time series is ranked first and never last. This is due to the process of surrogation which creates increased randomness within the time series when determinism is removed (Miller *et al.*, 2006; Small *et al.*, 2001; Theiler *et al.*, 1992). LyE and SampEn are both metrics scaled such that increased values are associated with random time series. If the LyE or SampEn values of an original time series rank last under nonparametric testing compared to the surrogates, then most likely the surrogation technique failed to generate time series that removed underlying deterministic structures. When the original time series is in a rank position of 1 (i.e., the lowest LyE or SampEn value), then the null hypothesis is rejected and the original time series is considered to have an underlying deterministic structure possibly due to chaos.

Many surrogation procedures utilize shuffling of the original measures either in the time domain or frequency domain (Theiler *et al.*, 1992). These techniques, however, may result in spurious conclusions when dealing with measures such as joint flexion/extension time series, which have a strong inherent periodicity (Miller *et al.*, 2006). For this reason, the pseudoperiodic surrogation (PPS) technique was utilized (Miller *et al.*, 2006; Small *et al.*, 2001). The PPS technique preserves intracycle dynamics (the structure within a single cycle), while destroying the intercycle dynamics (the structure contained from cycle to cycle) (Miller *et al.*, 2006). Unlike previous surrogation techniques, the PPS utilizes state space reconstruction and may be considered a random walk on the attractor. The result is a similar attractor in reconstructed state space and a similar time series compared to the original (Figure 1); however, with different intercycle fluctuations. Using the PPS technique, 19 surrogates were generated for both ankles of each subject for each of the 6 trials (1 trial per visit, 3 visits per prosthesis, 2 prostheses). Note that the original time series were only directly compared to the surrogate generated from that time series.

Analysis

SampEn and LyE were utilized as the discriminant metrics in the surrogation analyses to determine complexity of ankle motion. The LyE is a measure of how quickly similar points in state space diverge along their respective trajectories (Rosenstein *et al.*, 1993; Wolf *et al.*, 1985; Wurdeman and Stergiou, 2013; Wurdeman *et al.*, 2013a; Wurdeman *et al.*, 2013b). In terms of gait, it represents how quickly an independent point in the gait cycle fluctuates from other similar points in the gait cycle occurring during a different stride. The LyE is chosen for its use in previous studies by Wurdeman *et al.* (2013b) and Wurdeman (2013a) examining stride-to-stride fluctuations at the ankle in amputee gait as well as its basis in chaos theory, whereby the presence of a positive LyE is necessary for chaos (Wolf *et al.*, 1985). The method for the calculation of the LyE is outlined in greater detail in previous studies (Myers *et al.*, 2009; Wolf *et al.*, 1985; Wurdeman *et al.*, 2013a; Wurdeman *et al.*, 2013b). SampEn, a refinement of the original approximate entropy algorithm, quantifies entropy in the signal (Pincus *et al.*, 1991; Pincus, 1995; Richman and Moorman, 2000). In terms of entropy, a signal of low complexity will either have complete periodicity, in which case there is little to no entropy (i.e., SampEn $= 0$), or it is a completely random signal (i.e., SampEn $= \infty$). In practice, high complexity falls between these values and can be determined by comparison to healthy controls. SampEn is not the best suited for measuring stride-to-stride fluctuations in a quasi-periodic signal such as joint flexion/extension because the underlying periodicity can strongly affect the measure, leading to reduced values such that differences may be masked. However, it is attractive as a discriminant tool for surrogation analysis when using PPS because it does not analyze the movement within the reconstructed state space, thereby providing a different means of analyzing the original compared to the surrogate time series. More specifically, if PPS generates surrogate time series within the reconstructed state space, then the boundaries of the attractor of the original time series will possibly create strong enough bounds that the possibility for divergence of nearby neighbors, as calculated for LyE, may be restricted. The LyE is thus more influenced by the remaining intracycle dynamics which are preserved by PPS, whereas SampEn which is not based on cycles would not be as influenced by this. However, SampEn is not viewed as a sufficient discriminant metric because of noted potential limitations in its use for time series with strong underlying periodicity. Thus, both SampEn and LyE were applied. The technique for calculation of SampEn is outlined in greater detail elsewhere as well (Richman and Moorman, 2000; Yentes *et al.*, 2013). Briefly, SampEn is calculated by counting vector matches throughout the time series and comparing this as a ratio to the number of matches for a vector that is one unit larger (Richman and Moorman, 2000; Yentes *et al.*, 2013).

All ankle flexion/extension time series were ultimately cropped to 110 strides with the single exception of 1 subject that was only able to attain 70 strides in all data collections. Time series were cropped to 110 strides as this was the minimum amount of strides that all subjects were able to achieve except the individual that only took 70. The large discrepancy between this individual and the other 27 subjects was the reason for not cropping all trials to 70 strides. In addition, this study only compares original time series to their surrogate time series in a within subject design. The embedding dimension and time lag for each time series were calculated using the false nearest neighbor and average mutual

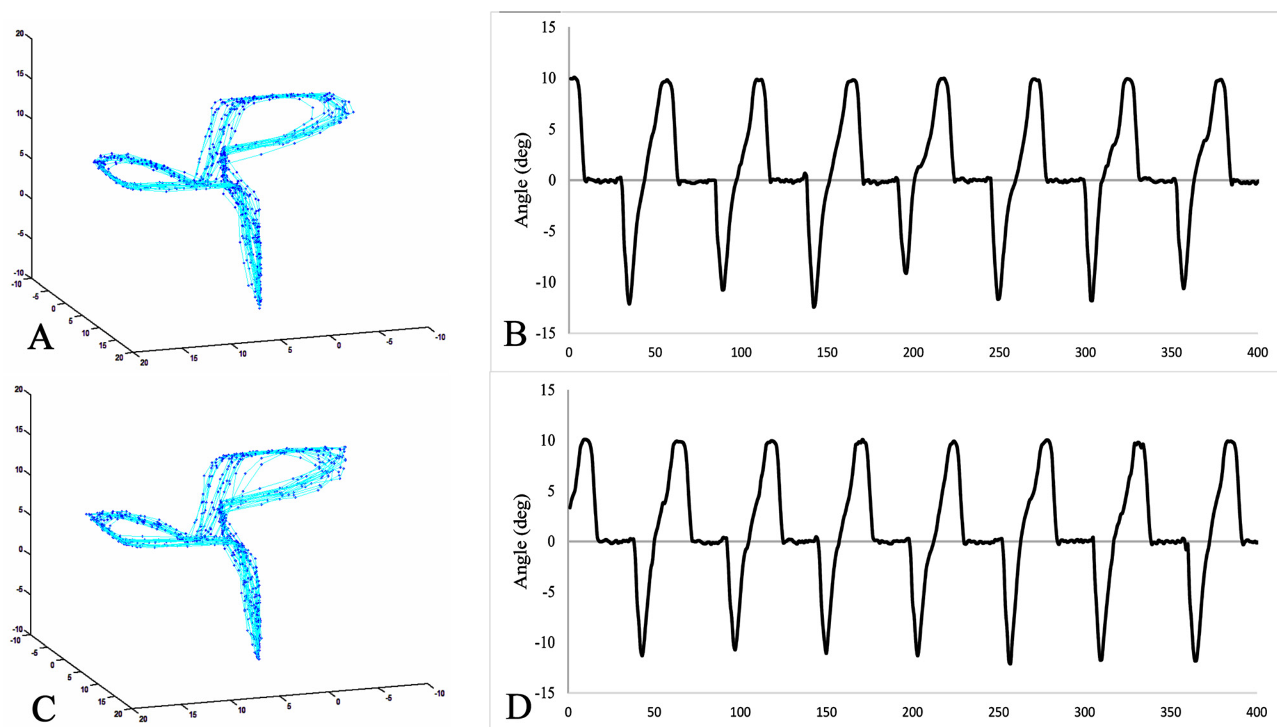

FIG. 1. The surrogate attractor resulting from the pseudoperiodic surrogation technique embedded into three dimensions (C) has a very similar appearance as the original prosthetic ankle attractor, also embedded here in three dimensions for visualization (A), despite the destroyed intercycle dynamics. The surrogate time series resulting from the pseudoperiodic surrogation technique (D) has a very similar appearance as the original prosthetic ankle flexion/extension time series (B) as well, despite the destroyed intercycle dynamics.

information algorithms, respectively (Abarbanel, 1996; Myers *et al.*, 2009; Wurdeman *et al.*, 2013b). PPS was then performed on each original time series, generating 19 surrogates for each time series.

For subsequent LyE calculations, all the time series were consequently embedded with the average dimension of 7 (Wurdeman, 2013a; Wurdeman, 2013b). The LyE was calculated for all original and surrogate time series of the prosthetic and sound ankles. Calculation of LyE requires several input parameters which were set to the following based on previous work (Wurdeman *et al.*, 2013a; Wurdeman *et al.*, 2013b; Wurdeman, 2013a; Wurdeman, 2013b): time evolution equal to 3 (Wolf *et al.*, 1985; Wurdeman *et al.*, 2013a; Wurdeman *et al.*, 2013b), max angle to replacement point equal to 0.3 radians (Wolf *et al.*, 1985; Wurdeman *et al.*, 2013a; Wurdeman *et al.*, 2013b), minimum scale length of 0.0001 (Wolf *et al.*, 1985; Wurdeman *et al.*, 2013a; Wurdeman *et al.*, 2013b), and maximum scale length of 0.1 times the maximum diameter of the attractor (maximum distance to selection of new nearest neighbor) (Wolf *et al.*, 1985; Wurdeman *et al.*, 2013a; Wurdeman *et al.*, 2013b). Similarly with SampEn calculations, all original and surrogate time series were analyzed (not in state space however). There are a few input parameters for SampEn that need to be set as well, which were determined using guidelines dictated by Yentes *et al.* (2013). As a result, the following parameters were utilized: vector length equal to 2, tolerance set at 0.2 times the standard deviation of the time series, and time lag equal to 1.

Original time series were tested against their surrogate counterparts using a nonparametric rank-order statistical test with an alpha value of 0.05. Any original time series not falling less than the 19 surrogates in their rank-order (and thereby falling in the outer 5%) were not considered significantly different from the surrogates and thus the null hypothesis could not be rejected. This procedure was performed for all subjects and for all visits in the laboratory.

RESULTS

In total, 56 surrogation analyses (28 subjects times 2 ankles) were performed for each of 6 total visits (visit 1, 2, and 3 for more appropriate prosthesis, and visit 1, 2, and 3 for less appropriate prosthesis).

LyE surrogation results

For the more appropriate prosthesis, only one surrogation test failed (out of 56 tests times 3 visits for total of 168 surrogation tests for more appropriate prosthesis), or a failure rate of 0.6%. A failed surrogation test means the null hypothesis is not rejected. This one failure was a subject's sound ankle movement at the initial fitting in which the LyE value for the sound ankle was slightly greater than one of the 19 surrogate time series (LyE original: 1.140, LyE surrogate: 1.117), resulting in rank position 2. Similar results occurred for the less appropriate prosthesis. In this case, only one surrogation test failed (again out of 168 surrogation tests for less appropriate prosthesis), or a failure rate of 0.6%. This was a different subject's prosthetic ankle (subject was bilateral amputee) than the previously mentioned subject. The trial was during the second visit in which again the LyE value for the ankle motion was slightly greater than one of the 19 surrogate time series (LyE original: 1.829, LyE surrogate: 1.773), resulting in rank position 2.

SampEn surrogation results

For the more appropriate prosthesis, there were 23 surrogation tests that failed (out of 56 tests times 3 visits for total of 168 surrogation tests for the more appropriate prosthesis; Figure 2), or a failure rate of 13.7%. Of the 23 failures, 7 occurred at the initial visit (out of 56 tests) or a 12.5% failure rate, 7 occurred at the second visit (out of 56 tests), or 12.5% failure rate, and 9 occurred at the final visit (out of 56 tests), or a 16.1% failure rate. For the less appropriate prosthesis, there were 33 surrogation tests that failed (out of 168 surrogation tests total for the less appropriate prosthesis), or a failure rate of 19.6%. Of the 33 failures, 12 occurred at the initial visit (out of 56 tests) or a failure rate of 21.4%, 10 occurred at the second visit (out of 56 tests) or a failure rate of 17.9%, and 11 occurred at the final visit (out of 56 tests) or a failure rate of 19.6%. Of the total 56 surrogation tests that failed in either the more appropriate or the less appropriate prosthesis, 100% were the prosthetic ankle and 0% was the sound ankle. This is a failure rate for the prosthetic ankle of 29.2%, as 56 surrogation tests failed out of 192 total tests (32 prosthetic ankles times 6 total visits).

DISCUSSION

The purpose of this study was to determine the underlying complexity found within transtibial amputee gait, with a focus on ankle motion based on significant findings at the ankle in previous work (Wurdeman *et al.*, 2013a; Wurdeman *et al.*, 2013b; Wurdeman, 2013a; Wurdeman, 2013b). To accomplish this task, individuals with transtibial amputation underwent 2 separate adaptation periods, one for 2 prosthesis setups. The prostheses were deemed "more appropriate" or "less appropriate" based on matching K-levels. The resultant ankle flexion/extension time series for the prosthetic and sound ankles were then analyzed using the PPS technique for underlying deterministic structure (Miller *et al.*, 2006; Small *et al.*, 2001). LyE and SampEn were then used as the discriminant metrics to detail differences between original and surrogate time series.

Following the use of LyE as a discriminant measure, only one trial each for the "more appropriate" and the "less appropriate" prosthesis failed surrogation. The low percentage of surrogation failures that this equates to (i.e., 0.6% for each prosthesis) would seem to be more of a spurious result. These findings provide evidence that the PPS technique did successfully work, meaning that from the original time series, surrogate time series from which underlying deterministic structure was removed were generated, resulting in time series that did measure to be more random. From these findings, it would seem that the prosthetic ankle and sound ankle, while having altered attractor divergence as evidenced by increased LyE compared to controls (Wurdeman *et al.*, 2013b), both display an underlying deterministic structure.

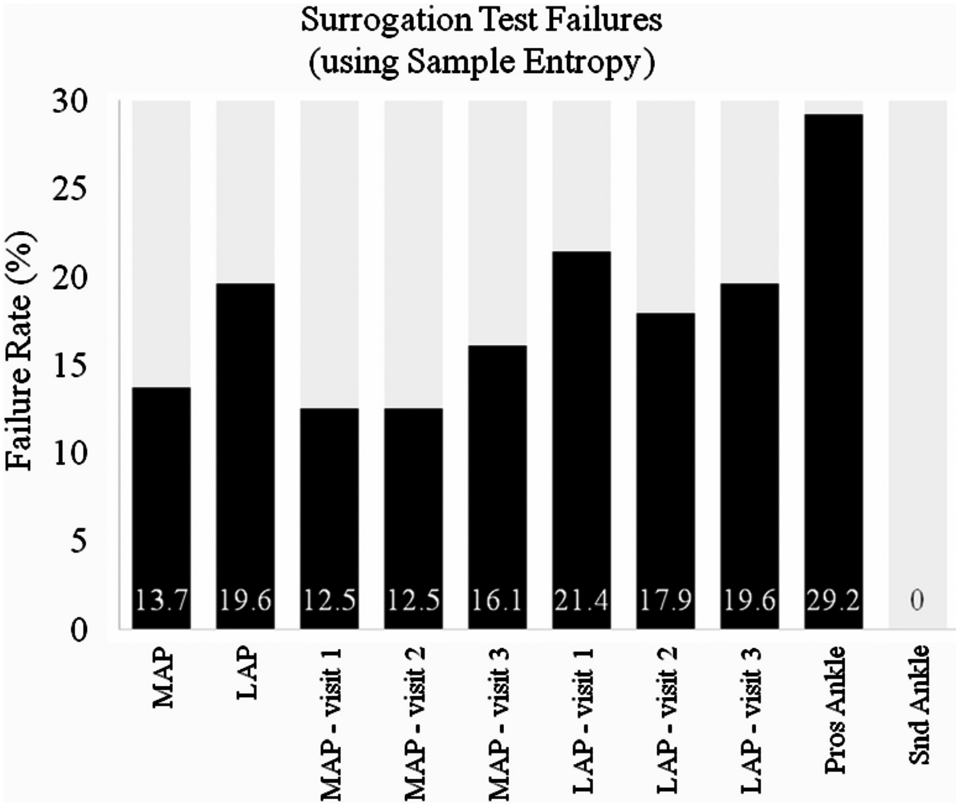

FIG. 2. The "less appropriate" prosthesis had a higher surrogation failure rate compared to the "more appropriate" prosthesis, meaning decreased complexity. There did not seem to be any effect across adaptation period. The prosthetic ankle (Pros Ankle) had a much greater surrogation test failure rate compared to the sound ankle (Snd Ankle), which had 0% failure rate. This means of the 56 surrogation tests that failed, all were the prosthetic ankle.

However, as noted, the vulnerability of LyE to intracycle dynamics which are not being destroyed in PPS (Miller *et al.*, 2006; Small *et al.*, 2001) may lead to false positives. A similar statement could be made for the "more appropriate" and "less appropriate" prosthesis designs, which seemed to have no impact on complexity when, in fact, this may be a result of the influence of intracycle dynamics on LyE calculation.

From the LyE results, it is possible to determine that the PPS technique (Small *et al.*, 2001) did, in fact, effectively destroy intercycle dynamics, resulting in surrogate time series that have increased random elements. But as noted, the LyE results may be compromised based on the fact that the intracycle dynamics of the time series are not being affected. The LyE is a geometric measure utilizing Euclidean distance measures (Myers *et al.*, 2009; Wolf *et al.*, 1985; Wurdeman *et al.*, 2013a; Wurdeman *et al.*, 2013b). If the intracycle dynamics are not being altered, then they will also influence the LyE calculation. Specifically, the bounded limitations of the attractor in the state space, commonly referred to as the neighborhood, create a problem with the generation of surrogate time series as they retain intracycle dynamics (Small *et al.*, 2001). The calculation of LyE for surrogates generated through PPS can only have a certain amount of divergence between trajectories based on the initial amount found within the original time series, or the intracycle dynamics. For example, consider two individuals walking several street blocks, with one in the street and the other on the sidewalk. They have a certain path of motion as they walk along, bounded by the limits of either the street or the sidewalk. Their trajectories could in essence have similar rates of divergence as they walk. For the generation of surrogates using the pseudoperiodic technique, a random walk along their attractor is performed. The individual in the street, however, has far greater space with which a random walk can occur permitting greater availability for increased stray. Random walks can be created from the path for the person on the sidewalk, but the boundaries of the sidewalk (analogous to boundaries of the attractor) will afford far less divergence. Despite this limitation of the use of LyE as a discriminant measure (i.e., calculation overpowered by intracycle dynamics), results from LyE calculation as a discriminant provide a strong finding that indeed the PPS technique does, in fact, work as intended. PPS did generate surrogate time series that had increased elements of randomness, which resulted in increased LyE values.

Using SampEn as a discriminant measure provides more valuable outcomes with regards to the hypotheses in this study. Based on discussion above, where LyE is a geometric measure utilizing Euclidean distance calculations (Wolf *et al.*, 1985), SampEn looks for vector matches within a time series (Richman and Moorman, 2000). The retained intracycle dynamics should similarly affect the SampEn as the intercycle dynamics because SampEn is not a cycle driven analysis, and thus its use following PPS can help to provide insight on underlying deterministic structure. It is possible to see from the SampEn results, there is a difference in complexity of the prosthetic ankle motion and the sound ankle motion. Every surrogation test that failed, thus displaying a lack of complexity, was for the prosthetic ankle motion. There were no surrogation test failures for the sound ankle. Furthermore, the failure rate was fairly high at nearly 1 out of 3 tests. From this, it would seem that the prosthetic ankle motion overall does not yield the complexity seen in the sound ankle motion. If the presence of complexity does provide greater adaptability and improved function, then this rate of slightly under 30% may be in part contributing to the high incidence of falls in amputees (>52% of amputees reported falling in previous year according to Miller *et al.* (2001)). Our study, however, did not survey fall history and as such this is only speculative.

It may be possible to enhance complexity through prosthesis design since the surrogation failure rate for the "more appropriate" prosthesis was lower than the "less appropriate" prosthesis. The difference of 13.7% to 19.6% is large, and considering limitations to the study, may be even greater. Specifically, with regards to prosthesis design being "more appropriate" or "less appropriate," this is a study limitation as this was highly dependent upon the referring physician and/or prosthetist's ability to properly categorize the individual based on the Medicare Functional Classification Levels (Gailey *et al.*, 2002) and the proper categorization of the prosthetic components with the largest emphasis on the prosthetic foot. In other words, the large majority, if not all the individuals, may not have had the *most* appropriate prosthesis design, which could have possibly reduced the 13.7% failure rate. And, the improved categorization of the individuals may have switched their category level, such that when it was considered a match between the person and componentry activity level, this may have actually been a mismatch and should have been considered "less appropriate." Nevertheless, our sample size ($n = 28$) would seem to be large enough to provide results able to overcome this limitation. Unfortunately, adaptation does not seem to be able to enhance complexity as there was little change from visit to visit in terms of changes in failure rate. Under the present findings, it may not be necessary for a clinician or researcher to wait to assess prosthetic feet. However, our study design only utilized an unstructured neuromuscular learning period, where the only learning was through the individual taking the device and wearing it. Structured neuromuscular learning in the form of physical therapy may be able to improve this by giving guidance so that poor mechanics are not simply being reinforced with each step.

The decreased complexity associated with the prosthetic ankle compared to the sound ankle highlights the presence of decreased adaptability for persons with transtibial amputation, specifically with increased focus on poor control of the non-biological joint. It is not surprising that the non-biological joint has worse control than the biological ankle with the lack of physiological structures. However, this study is the first to report this poor control resulting in reduced complexity, which is interpreted to be decreased adaptability. Such decreased complexity due to amputation is consistent with increased rates of falling (Miller *et al.*, 2001). Thus, it should be hypothesized that increasing complexity would provide increased adaptability and help individuals to better ambulate with reduce problems such as falling. It does appear that with improved prosthesis prescription it may be possible to begin to restore complexity to a richer level. This is highlighted by our findings of increased complexity with a "more appropriate" prosthesis, which under the current experimental design should be considered a bettered prescribed prosthesis as it is better aligned with current prosthesis prescription paradigms (despite the immense ambiguity currently associated with prosthesis prescription (Hofstad *et al.*, 2004)). Furthermore, it may be possible to use complexity as an outcomes assessment, noting the increased complexity with improved prescription. This practice, however, is very limited at this time due to translation of such technical concepts to the clinical setting and the computational time associated with such practice.

In addition to the limitation already addressed regarding classification of individuals and prosthetic components, there are other limitations to this study. While we attempted to have subjects that were K2 and below and K3 and above (the break between these classification levels marks the largest break in terms of reimbursement and functional level), we were unable to successfully recruit any individuals that were K2 or lower level. As a result, the findings of "more appropriate" versus "less appropriate" may not be the case for K2 patient wearing a prosthesis of higher activity level. Future work will need to investigate K2 patients to determine if similar results are found. Furthermore, we were able to secure multiple high activity feet in order to properly fit all subjects. However, for the low activity feet, with the exception of 1 subject that wore a Walktek foot (K2 foot from Freedom Innovations, Irvine, CA, USA), all low activity feet were SACH feet (The Ohio Willow Wood Company, Mt. Sterling, OH, USA). This was done to improve study logistics such that once a subject was enrolled it was only necessary to acquire high activity feet, which due to category levels and sizes have a much greater variance. Consequently, our findings may simply be due to differences between high activity feet and SACH feet, and, in fact, SACH feet are inhibiting complexity. However, for the single subject that wore a Walktek foot, out of the 3 visits with this prosthesis setup, 2 failed surrogation testing (with SampEn). Thus, it is not likely to be a finding limited to SACH feet. Importantly, while all subjects wore appropriate prostheses for their own prescribed prosthesis, and thereby wearing similar category feet as were used for the "more appropriate" design, prosthesis setup was done in a manner to prevent individuals from wearing the same foot as their prescribed prosthesis. This was done to prevent experience with either prosthesis setup.

Next, it is unclear which discriminating measure is best for surrogation analyses. To overcome this obstacle, we utilized two nonlinear analysis measures that are very different; the first, LyE, is a measure that requires state space reconstruction, which is the same as the PPS technique used to create surrogates, and the second, SampEn, does not require state space reconstruction. Thus, it is possible to understand how random surrogates generated from one time series do not necessarily have similar mean LyE values as those generated from a different time series, despite both being random.

LyE values do provide good evidence that, in fact, the PPS technique does work, generating time series from the original that is without the deterministic intercycle structure. Furthermore, we chose a 3 week adaptation period as the scant literature available dictates this to be a sufficient adaptation period for an individual adapting to a prosthesis (English *et al.*, 1995). It is possible that to see an effect (based on SampEn surrogation results), more time is needed. However, we chose not to extend the adaptation period to mitigate subject dropout rate and increase initial recruitment, but future work should consider this limitation. Finally, all subjects enrolled were experienced prosthesis users. Results for adaptation, and thereby neuromuscular learning, may be improved in investigating new amputees.

Another limitation is the sole investigation of the prosthetic and sound ankle joints. While proximal joints have been found to be altered due to prosthetic gait (Beyaert *et al.*, 2008; Grumillier *et al.*, 2008; Kovac *et al.*, 2010; Prinsen *et al.*, 2011), the associated computational time for generating the surrogate time series (8–12 min. per surrogate) and for calculating LyE (2–3 min. per time series), made it impractical to include all lower limb joints. Therefore, we chose to only examine the ankle joint based on the significant findings from our previous work (Wurdeman *et al.*, 2013b; Wurdeman, 2013a). However, future work should consider more proximal joints as these joints may reveal more changes in complexity analogous to more standard gait metrics such as joint moments and powers. Furthermore, the prosthetic ankle joint is noted as not being a true joint as instead prosthetic feet tend to deform and then recoil which can cause error in joint angle calculations. However, as noted previously (Wurdeman *et al.*, 2013a), the LyE is examining divergence within the reconstructed attractor, which represents the motion and is not concerned with the absolute values of joints. In other words, the LyE is not affected by whether the joint location is off and under/overestimates the magnitude of the ankle angle.

CONCLUSION

Findings from this study indicate complexity in walking is a phenomenon that may be compromised following amputation and subsequent prosthetic rehabilitation. The loss of complexity would lend itself to decreased adaptability by the amputee when walking, which may result in decreased functionality (Lipsitz and Goldberger, 1992; Lipsitz, 2002; Lipsitz, 2004). It is possible that improved prosthetic prescription, or the ability to more accurately match a person with the appropriate prosthesis, may yield improved complexity in walking. Adaptation, alone, to a new prosthesis does not seem to lend itself to improved complexity in amputee gait. Future work is needed to investigate lower activity level amputees as well as non-experienced prosthesis users.

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